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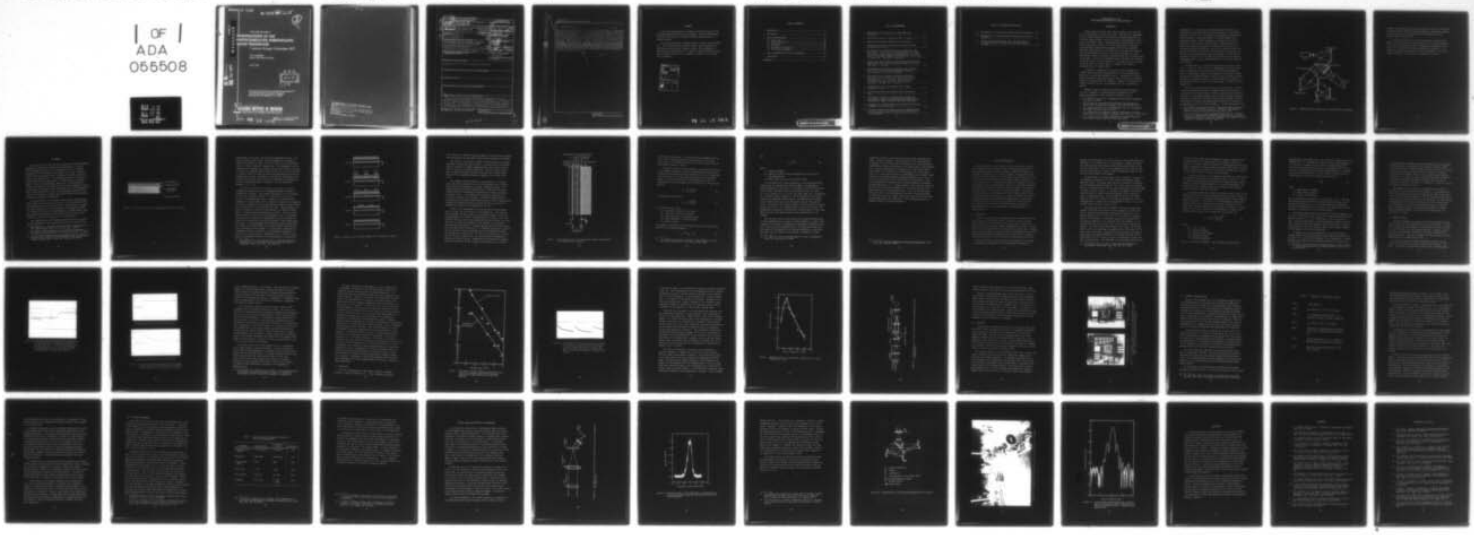

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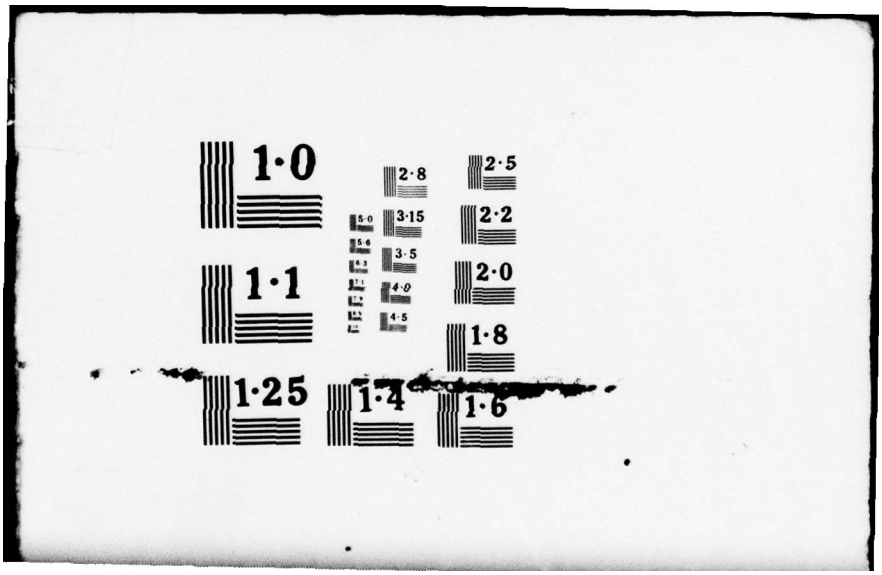
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Final Scientific Report

INVESTIGATIONS OF THE PHOTOCONDUCTOR-THERMOPLASTIC IMAGE TRANSDUCER

1 January through 31 December 1977

W.S. COLBURN
Radar and Optics Division

MAY 1978

Directorate of Electronics & Solid State Research
Air Force Office of Scientific Research
Bolling AFB, Washington, D.C. 20332

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A basic research effort was performed to investigate the use of the photoconductor-thermoplastic (PTP) recording medium as an incoherent-to-coherent transducer that serves as a real-time input device for an optical data processor. The principle of operation of the PTP recording medium is reviewed with a brief discussion of nonlinearities. We describe experimental investigations of the write-time, repetitive writing, resolution,

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response to a CRT input, and addition of an integral grating. Using parall plane charging we were able to carry out write cycles (charge, expose, and develop) in less than 10 msec. With the thermoplastic biased at an elevate temperature, repetitive recording was demonstrated at a rate of 2.5 cycles/ sec. We incorporated the PTP transducer into an advanced optical processor that used holographic optics to form a lightweight real-time optical data processor. The photoplastic transducer is characterized by good exposure sensitivity, high resolution, and simple construction. Because development and erasure occur only upon deliberate application of heat, the transducer is well suited to applications that require image retention before and duri readout. Regardless of the spectral sensitivity of the photoconductor, rea out can be at any wavelength.

FOREWORD

This report was prepared by the Radar and Optics Division of the Environmental Research Institute of Michigan. The work was sponsored by the Air Force Office of Scientific Research under Contract No. F44620-76-C-0053.

The report covers work performed between 1 January and 31 December 1977. The contract monitor is Captain John A. Neff, Directorate of Electronics and Solid State Sciences, Bolling AFB, Washington, D.C. The principal investigator is W. S. Colburn. Major contributors to the effort reported herein are W. S. Colburn, M. Gredell, C. D. Leonard, and J. Upatnieks.

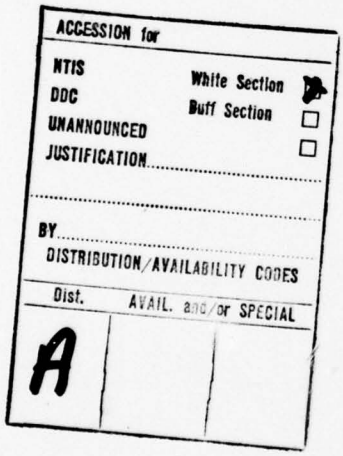

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

INVESTIGATIONS OF THE PHOTOCONDUCTOR-THERMOPLASTIC IMAGE TRANSDUCER

1 INTRODUCTION

Certain signal processing tasks require making a very large number of computations in a short time period. One means of accomplishing this is to take advantage of the parallel processing capabilities of an optical data processor, which can process a two-dimensional array of data at the speed of light. Although optical data processing is used with a high degree of success in certain applications, traditional processing uses conventional photographic film for data insertion. Additional applications that could make use of the large data capacity of optical processors also have a real-time requirement; for these applications a means is required of inserting data into the signal plane in real-time. This can be accomplished with a transducer that converts electrical signals to optical signals or, since most optical processing is carried out with coherent light, a transducer that converts incoherent light to coherent light.

In addition to operating in real-time, an input transducer to a coherent optical processor should display data in a two-dimensional format with a large space-bandwidth product. Furthermore, the device should be capable of repeated cycling, so that the data can be written, erased, and rewritten onto the transducer. Finally, to form part of a coherent optical processor, the transducer must be of high optical quality.

Although a number of materials and devices have shown promise for such a transducer, the photoconductor-thermoplastic or PTP device [1-5] appears to have the greatest potential for the

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1. J.C. Urbach and R.W. Meier, "Thermoplastic Xerographic Holography," Appl. Opt. 5, (1966).
2. L.H. Lin and M.L. Beauchamp, "Write-Read-Erase in Situ Optical Memory Using Thermoplastic Holograms," Appl. Opt. 9, 2088 (1970).
3. T.L. Credelle and F.W. Spong, "Thermoplastic Media for Holographic Recording," RCA Review, 33, 206 (1972).
4. W.S. Colburn and E.N. Tompkins, "Improved Thermoplastic Photoconductor Devices for Holographic Recording," Appl. Opt. 12, p. 2934 (1974).
5. W. S. Colburn and J.B. DuBow, "Photoplastic Recording Materials," Final Technical Report AFAL-TR-73-255, August 1975.

implementation of a practical real-time transducer that meets the requirements of high resolution, high optical quality, recyclability, simplicity, and low cost. PTP devices are characterized by relatively good sensitivity, high optical quality, and stable readout until intentional erasure. Since information is written onto the device optically, it can be written serially with a scanning system or in parallel by conventional imaging. The device thus functions as an incoherent-to-coherent transducer. Since the recording is stable until erasure, the readout illumination will not affect the device and thus may have the same wavelength as used for recording. PTP devices are especially attractive for some applications because they are compact, lightweight, and are easily fabricated simply by coating the materials from solution.

The development of a real-time PTP incoherent-to-coherent transducer is part of a research effort to demonstrate real-time processing in an advanced optical processor that by employing holographic optics is lightweight, compact, and inexpensive, as required in applications such as terminal guidance. Figure 1 shows a possible configuration for the advanced processor with a real-time input transducer. The advanced optical processor was developed under a separate, parallel program [6].

This report describes the results of a research effort to develop a real-time incoherent-to-coherent transducer that forms the input to a coherent optical data processor. Under the first phase of the research program [7], we developed techniques for recording incoherent images in real-time on a PTP device that uses parallel-plane charging, achieved a write-time of 30 msec, and demonstrated correlation in a matched filter processor with the PTP input transducer. In the second phase of the

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6. J.R. Fienup, Final Technical Report, "Optical Processors Using Holographic Optical Elements," Report No. 119400-2-F, Environmental Research Institute of Michigan, Ann Arbor, April 1978.

7. W.S. Colburn and B.J. Chang, Interim Scientific Report, "Investigations of the Photoconductor-Thermoplastic Devices As An Incoherent-to-Coherent Transducer," Report No. 119500-1-T, Environmental Research Institute of Michigan, Ann Arbor, April 1977.

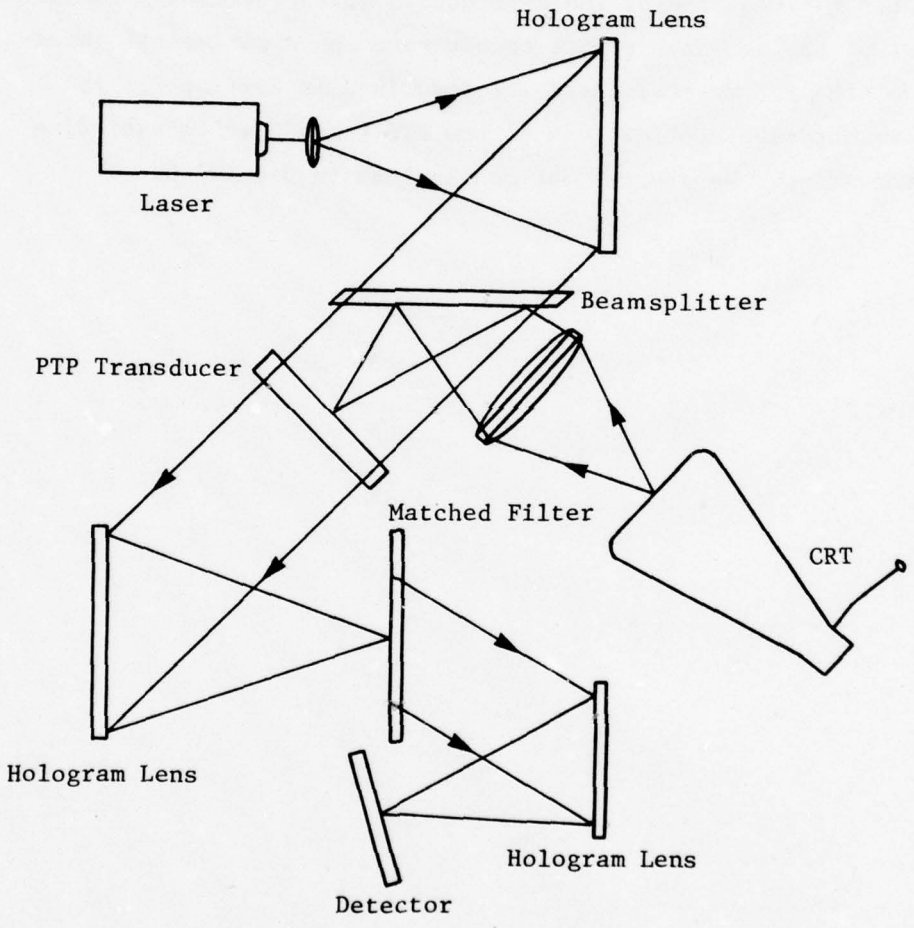

Figure 1. Advanced Optical Processor With a Real-Time Input Transducer.

program, we decreased the write-time to less than 10 msec, investigated a television input, explored screening methods to incorporate a grating into the PTP device, and integrated the PTP transducer into the advanced optical processor [6].

In the next section, we review the principles of operation and present a brief discussion of the diffraction of the readout illumination. Most of the research effort concentrated on experimental investigations of the PTP device; these are described in Section 3. In Section 4 we describe applications of the PTP transducer to real-time optical processing. We present our conclusions in Section 6.

2
PTP DEVICE

In this section we review the basic operation of the photoconductor-thermoplastic (PTP) device and discuss the diffraction of light by surface deformations formed in the thermoplastic layer. The basic configuration of the PTP device (see Figure 2) is a glass substrate coated in successive layers with a transparent electrode, a photoconductor, and a thermoplastic. The transparent conductor serves both as a ground plane when the thermoplastic is charged and as a resistive heater to raise the thermoplastic temperature. The photoconductor converts the intensity distribution of the incident illumination into a corresponding electrostatic field distribution across the thermoplastic. After a brief application of heat, the thermoplastic retains the information as thickness variations which can be erased by sufficiently raising the thermoplastic temperature.

The photoconductor is the organic polymer poly-n-vinylcarbazole (PVK), usually sensitized with the dye 2,4,7 trinitrofluorenone (TNF) [8] although other dyes can be used [9,10]. Photoconductor coatings are usually prepared from solutions made by dissolving PVK and TNF in a suitable solvent such as tetrahydrofuran. PVK/TNF readily forms thin amorphous photoconductor films characterized by good exposure sensitivity, high dark resistance, and low scatter noise.

Many thermoplastics with different characteristics are suitable for the thermoplastic layer; materials that have been used include

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8. R.M. Schaffert, "A New High-Sensitivity Organic Photoconductor for Electrophotography," IBM J. Res. & Devel. 15, 75 (1971).
9. R.F. Bergen, "Characterization of a Xerographic Thermoplastic Holographic Recording Material," Phot. Sci. & Eng. 17, 473 (1973).
10. K. Kriz, "Spectral Response and Sensitometric Curves of Doped Poly-N-Vinylcarbazole Films in Electrophotography Under Positive and Negative Charging Modes," Phot. Sci. & Eng. 16, 58 (1972).

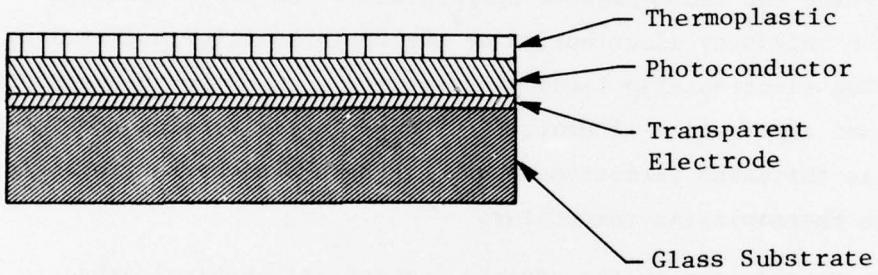

Figure 2. Cross Section View of a Photoplastic Device (Not to Scale).

polystyrenes, ester resins, and specially synthesized polymers. The material should normally have a softening temperature low enough to deform after modest heat input, yet not so low as to allow spontaneous erasure at normal operating temperatures. The thermoplastic must be resistant to crosslinking and oxidation during the write/erase cycling, it should form films with high optical quality, and it should be soluble in a simple solvent that does not affect the photoconductor during the thermoplastic coating. Although in a few cases the thermoplastic was a highly stablized ester resin, in most of the modulator investigations, we used a styrene/methacrylate copolymer of the type described by Anderson, et. al. [11].

The basic function of the PTP device is to convert a spatial illumination distribution into a corresponding spatial variation in thermoplastic thickness. The standard write/erase cycle is a sequence of five steps as shown in Figure 3. In the first step, the free surface of the thermoplastic layer is charged to a uniform positive potential of several hundred volts. During the charging, the transparent electrode is grounded so that an equal amount of negative charge collects at the lower surface of the photoconductor layer. After charging, the device is exposed; in regions of high exposure, the negative charges move to the photoconductor-thermoplastic interface. Since the charge density on the free surface of the thermoplastic layer is unchanged, the electrostatic fields in the thermoplastic are also unchanged (by Gauss' Law), and therefore the surface potential of the exposed region is reduced. A second charging step restores the original uniform surface potential by adding charge to the exposed areas, increasing the local electrostatic field strength. In this manner a distribution in illumination has been converted to a corresponding distribution in electrostatic force across the thermoplastic layer. When the thermoplastic is subsequently heated to its softening point, electrostatic

11. H.R. Anderson, Jr., E.A. Bartkus, and J.A. Reynolds, "Molecular Engineering in the Development of Materials for Thermoplastic Recording," IBM J. Res. & Dev., 15, 140 (1971).

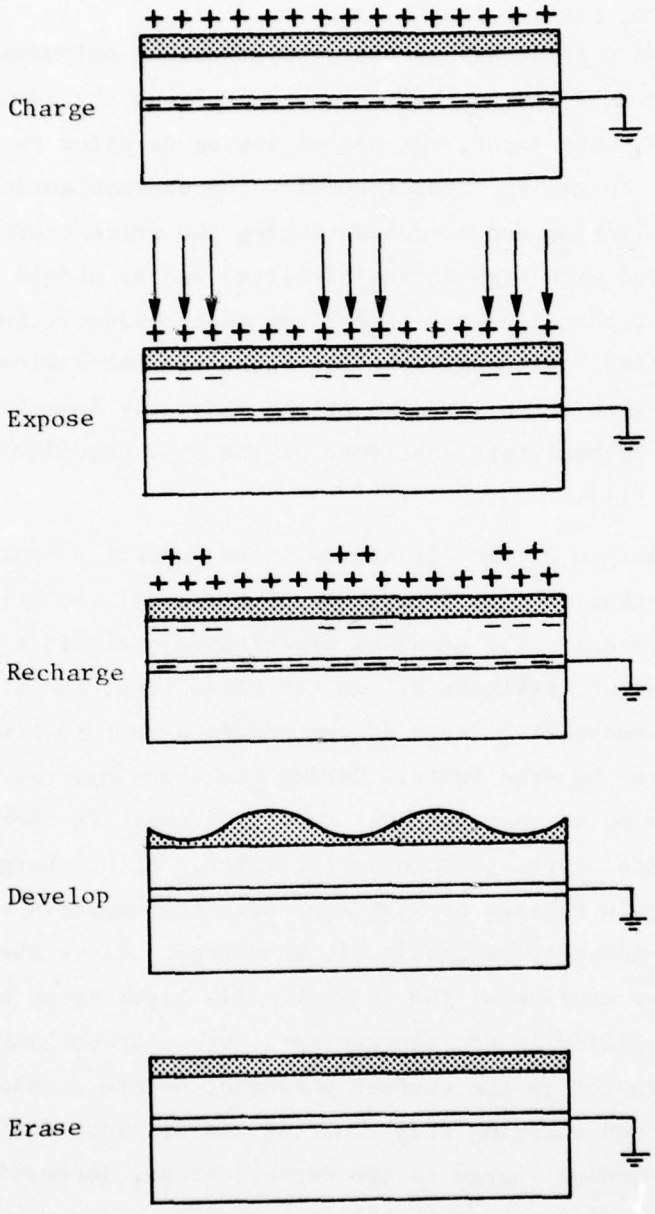

Figure 3. Normal Record and Erase Sequence for a Photoplastic Device.

forces cause it to deform as shown in Figure 3, with the heavily exposed areas decreasing, and the lightly exposed areas increasing in thickness.

The device is now ready for readout, and will retain the recorded information indefinitely until erasure. In the erase step, the thermoplastic is heated to a higher temperature than in the develop step in order to lower its electrical resistivity. The electrostatic fields then collapse and surface-tension forces restore the original smooth profile of the thermoplastic surface, readying it for another write cycle.

The standard five-step sequence is often modified. We usually expose the device during part or all of the charging, with the charge and recharge steps merged into one longer charging operation. The recharge step may overlap the develop step, in which case continued charging during the thermoplastic deformation may enhance the amount of surface relief. It is possible and occasionally preferable [5] to omit the recharge step altogether. Credelle and Spong achieved recordings characterized by high signal-to-noise ratios by simultaneously charging and exposing during and following the erase step with new deformations forming as the thermoplastic cools [3].

In most of our investigations we used the parallel-plane method [4,5] to charge the free surface of the thermoplastic. With parallel-plane charging, the device appears as indicated in Figure 4, with the gap approximately 50 μm wide. Charging requires voltages on the order of 700 to 900 volts, and can be accomplished in times as short as 1 msec. The device is complicated somewhat by the addition of the charging electrode which must provide a constant gap spacing, and by the requirement that the gap must be dust free. In addition, the gap must be filled with an inert gas to prevent degradation of the thermoplastic during the charging and heating cycles. To simplify our experimental investigations, we built a special test cell that provides an atmosphere of dry argon for the PTP device. Ultimately we would expect the charging plate to be sealed to the PTP substrate with an inert gas in the gap,

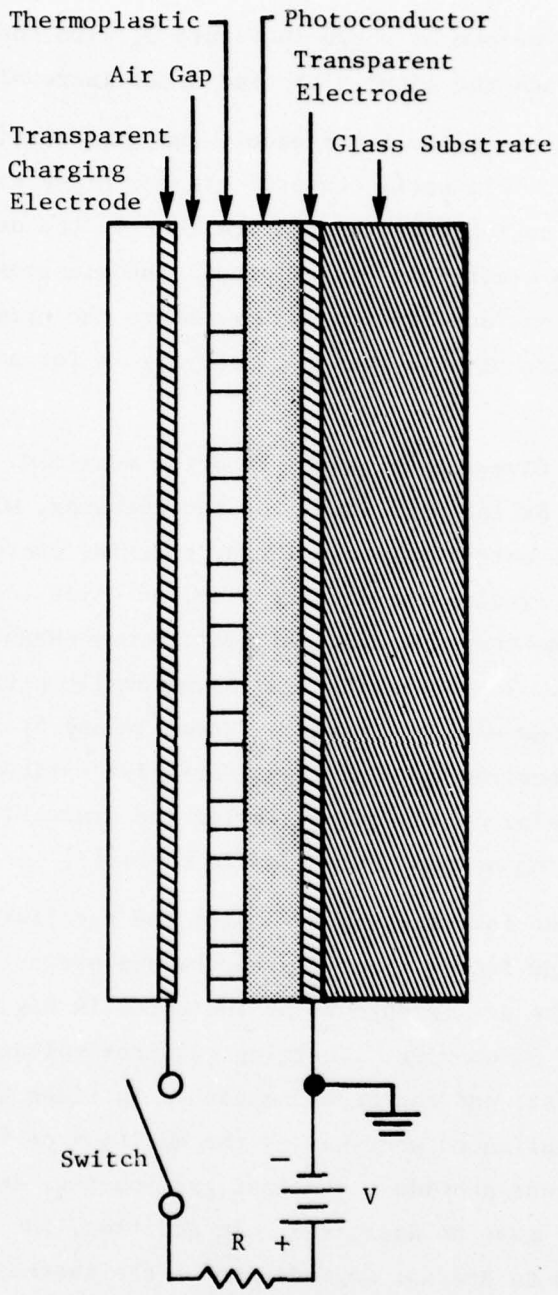

Figure 4. Cross Section View of the Photoplastic Device with Parallel-Plane Charging (Not to Scale).

precluding the requirement for an external inert atmosphere and test cell. Such a configuration would also prevent dust or dirt from collecting on the thermoplastic surface, and forms a device that has hard external surfaces of glass.

The surface relief of the thermoplastic layer modulates the phase of the readout illumination, both in transmission and in reflection. Following the development of Urbach and Meier [12], let us assume that the surface relief is a simple grating structure with a sinusoidal profile. The incident light will be diffracted into a series of transmitted and reflected orders, with the intensity of the nth order given by

$$I_n = k_t^2 \, J_n^2 \left(\frac{\phi_t}{2} \right) \tag{1}$$

for transmitted orders and by

$$I_n = k_r^2 \, J_n^2 \left(\frac{\phi_r}{2} \right) \tag{2}$$

for reflected orders, where

k_t = amplitude transmission coefficient
k_r = amplitude reflection coefficient
ϕ_t = phase modulation of transmitted light
ϕ_r = phase modulation of reflected light
J_n = Bessel function

The argument of the Bessel function differs for the two cases, and is given by the following expressions:

$$\phi_t = \frac{2\pi}{\lambda} (n_m - 1)h \tag{3}$$

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12. J.C. Urbach and R.W. Meier, "Properties and Limitations of Hologram Recording Materials," Appl. Opt. 8, 2269 (1969).

and

$$\phi_r = \frac{4\pi}{\lambda} h \qquad (4)$$

where

λ = readout wavelength

n_m = refractive index of the recording material (in our case, the thermoplastic)

h = peak-to-peak excusion of the surface relief.

For a grating with a single frequency f_o, the various diffracted orders $J_n(\phi)$ will propagate at different angles, corresponding to spatial frequencies of nf_o where n is the number of the diffracted order. We are usually interested in the first diffracted order, for which n = 1; the intensity at n = 0 is the zero order light that is transmitted (or reflected) without diffraction. For no absorption or reflection losses and a sinusoidal surface profile, the maximum fraction $[J_1^2(\phi)]$ of the incident light that can be diffracted into the first order is 33.9%. In practice, k_t^2 is usually between 0.5 and 0.8 and k_r^2 is usually between 0.04 and 0.1. For modulation that is more nearly linear, the thermoplastic deformation is usually kept relatively small, in the range where the first order Bessel function varies approximately as its argument.

For the more practical case in which the recorded information has a finite bandwidth about a carrier or offset frequency f_o, there is the possibility of overlap of information corresponding to different orders, and of distortion due to intermodulation. The diffracted orders will not overlap if the bandwidth of the recorded information is less than $f_o/3$ (Ref. 13), but because of the inherent nonlinearity of phase

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13. D.G. Falconer, "Role of the Photographic Process in Holography," Phot. Sci. & Eng. 10, 133 (1966).

modulation, the first order diffraction will include intermodulation terms. Although a number of terms contribute to the intermodulation distortion, it can be shown that the amplitude of the most significant intermodulation term is proportional to the third power of the modulation (ϕ^3). Since the amplitude of the desired first order diffraction is proportional to the first power of the modulation (for small modulation), it is clear that noise due to intermodulation can be made a small fraction of the desired signal by keeping the modulation low, but at the cost of accepting low first order diffraction efficiency. (Since the intermodulation distortion results from the inherent nonlinearity of phase modulation, it is a problem common to any device that modulates the phase of the incident illumination.) Two further points can be made concerning the intermodulation noise. First, as has been noted previously [12,14] the exact magnitude and form of the noise depends on the actual form of the signal itself, and second, some of the lesser intermodulation terms are suppressed if the recording material has a bandpass response to spatial frequencies.

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14. W.T. Cathey, Optical Information Processing and Holography, Wiley & Sons, New York, pp. 68-70.

3
DEVICE INVESTIGATIONS

The major portion of the research effort concentrated on experimental investigations of the PTP device, including investigations of the minimum write-time, repetitive writing, resolution, response to a CRT input, and addition of an integral grating. Using parallel-plane charging and a photoconductor with increased electron mobility, we were able to perform complete write cycles (charge, expose, and develop) in less than 10 msec. We demonstrated repetitive recording at a rate of 2.5 cycles/sec with the thermoplastic biased at an elevated temperature. We measured the frequency response of the PTP transducer and verified its resolution as an incoherent-to-coherent transducer. Although we recorded an image on the transducer from a CRT, inefficiencies in the optics required lengthy exposures. In order to eliminate the need for a separate grating, we investigated two approaches to incorporating the grating into the PTP device, but achieved only partial success. We conclude this section with a brief discussion of the general performance of the PTP recording medium, including comments on the medium lifetime.

3.1 WRITE-TIME

The use of parallel-plane charging allowed us to demonstrate rapid write sequences of less than 10 msec. In order to control the PTP device functions with millisecond precision, we built a solid-state timing circuit that provides complete flexibility and control in setting the durations and separations of all the write and erase steps. Although the low voltage timing circuits occasionally misfired when the relatively high charging voltage was switched, we were able to obtain reasonably consistent operation by careful attention to shielding and lead dress.

Rapid development of the thermoplastic recording can be realized by maintaining the thermoplastic at its deformation temperature, by

heating the thermoplastic with a short pulse of the required energy and duration, or by a combination of the two methods. Maloney and Gravel [15] used the pulsed heat method to demonstrate develop times of less than one millisecond. Since in this experiment we were concerned only with the time required to record a single thermoplastic image, we also used the pulsed method for development.

The application of a fixed amount of heat (required to develop the thermoplastic deformations) in a short time period requires a large peak power input. The energy input required to develop the thermoplastic recording is minimized through the use of short pulses [15] because there is a significant heat flow into the substrate when the pulse length is longer than about 10 msec. A reduction, for example, in the pulse length from 100 to 10 msec reduces the required develop energy by a factor of approximately two. Further reduction in the pulse length appears to have little effect on the energy requirement [15]. In our investigations, we found that for pulse lengths of 10 msec or less, the required develop energy was about 2 J/cm^2.

The large peak power levels required by short pulse lengths may severely stress the transparent electrode, assuming, of course, that heat is supplied through resistive heating of the electrode. If we assume a heated area of 1.0 cm^2, then a 2 J heat pulse is required to develop the recording; for continuous cycling (in the pulsed mode), the average temperature of the substrate will rise somewhat, so the required heat input will be less, say 1 J (more will be required for erasure). If the heat pulse has a duration of 0.1 msec, the required power is 10^4 watts, requiring, for example, 30a at 330 v into 10 Ω or 10a at 1000 v into 100 Ω. Ignoring the task of providing this kind of pulsed power, the current densities in the heating electrode will be approaching 10^5 a/cm^2, and will be near or exceeding the current capacity of the electrode. The uniformity of the electrode resistivity can

15. W.T. Maloney and R.L. Gravel, "Submillisecond Development of Thermoplastic Recordings," Appl. Opt. 13, 2471 (1974).

be quite critical under these circumstances, since a localized region of high resistivity can become quite hot, increase in resistance because of a positive thermal coefficient of resistivity, and eventually undergo catastrophic failure caused by excessive temperatures or voltage drops. Similarly, the electrode contacts must be established carefully to avoid local regions or points of high resistance.

To reduce the stress on the transparent electrode of our PTP device, we reduced the active area of the devices from 10 × 10 mm to 3 × 3 mm for these investigations, decreasing both the energy and power requirements by a factor of approximately 10. The energy requirement of the develop pulse was, therefore, about 0.2J, and for a pulse length of 2 msec, the power requirement was 100 w.

In achieving rapid write sequences in which we require that the time between the exposure and develop functions be short, we must consider the mobilities of the charge carriers generated within the photoconductor during the exposure. The exposure of the photoconductor creates hole-electron pairs; these charge carriers then drift according to their charge type under the influence of the electric field due to the initial charge step. Both the hole and electron mobilities μ depend on the electric field strength and the temperature in the manner [5]

$$\mu = \mu_o \exp \frac{-(E_o - BE^{1/2})}{k_b T_{eff}} \tag{5}$$

where

$T_{eff} = (1/T) - (1/T_o)$
E_o = activation energy
E = electric field strength
k_b = Boltzmann constant
T = absolute temperature

and μ_o, B, and T_o are constants. The individual hole and electron

mobilities have been shown [16] to vary strongly but oppositely with the PVK/TNF ratio. At a PVK/TNF molar ratio of 10 and a field strength of 5×10^5 v/cm, for example the hole mobility is approximately 10^{-6} cm^2/volt-sec and the electron mobility is approximately 10^{-9} cm^2/volt-sec [16]. The importance of the charge carrier mobility is clear when we calculate the transit time τ for the carriers to drift across the photoconductor film, where the transit time is given by

$$\tau = \frac{d}{\mu E} \tag{6}$$

where

d = photoconductor thickness

μ = charge carrier mobility

E = electric field strength.

For our calculation, we assume d to be 5 μm and E to be 5×10^5 v/cm. Using the mobilities given above, the transit time for holes is 10^{-3} sec and for electrons 1 sec. At our usual sensitizer concentration in which the PVK/TNF molar ratio is about ten we see that the electron mobility is insufficient for a rapid write sequence.

Doubling the TNF concentration increases the electron mobility from 10^{-9} to 2×10^{-8} cm^2/volt-sec, a factor of 20 while decreasing the hole mobility from 10^{-6} to 6×10^{-5} cm^2/volt-sec, a factor of only 1/1.6 [16]. With this modification to the photoconductor formulation and the use of relatively thin photoconductor layers, we were able to achieve electron transit times short enough to permit delays between charging and development of only a few milliseconds.

To simplify the write-time measurement, we used a continuous exposure during the test, monitoring the first order diffraction with a photodetector to ascertain the formation of the thermoplastic recording. We made the recording of the interference pattern of two plane waves

16. W.D. Gill, "Drift Mobilities in Amorphous Charge-Transfer Complexes of Trinitrofluorenone and Poly-n-vinylcarbazole," J. Appl. Phys., 43, 5033 (1972).

of coherent light to minimize the optical complexity of the experiment. The exposure was at a wavelength of 633 nm and at a typical energy level of 500 ergs/cm^2. Figure 5 shows oscilloscope traces of the charge voltage and the diffracted signal, with a time base of 1 msec/div. The lower curve in Figure 5 shows a 2 msec charge pulse; following a short delay, a 1.5 msec heat pulse was applied (not shown in Figure 5) to develop the hologram. The upper curve shows that the onset of diffraction followed the initiation of charging by 5.2 msec and that the recording was complete by 6 msec.

The dynamics of the response to the developing heat pulse are indicated by the oscilloscope traces in Figure 6. In this figure, the lower curves represent the heating voltage and the upper curves represent the diffracted signal intensity. For a 2 msec heat pulse, there is a lag of about 1 msec before the onset of diffraction. We also see that the diffracted signal continues to increase for a brief period while the thermoplastic is still hot following the cessation of the heat pulse. Figure 6b shows the case where the heat input is excessive and the deformation begin to decay before the thermoplastic cools sufficiently to harden.

3.2 REPETITIVE WRITE

Because development and erasure occur only upon deliberate application of heat, the PTP transducer realizes certain benefits. An image can be scanned onto the transducer at a relatively slow rate, and when the scan is complete, the entire image developed. Secondly, readout can be at any wavelength, regardless of the spectral sensitivity of the photoconductor. Finally, the image is retained indefinitely during readout until it is intentionally erased.

On the other hand, the thermal requirements introduce certain restrictions, especially for rapid cycling of the transducer. The write cycle itself is limited by the rate at which the thermoplastic

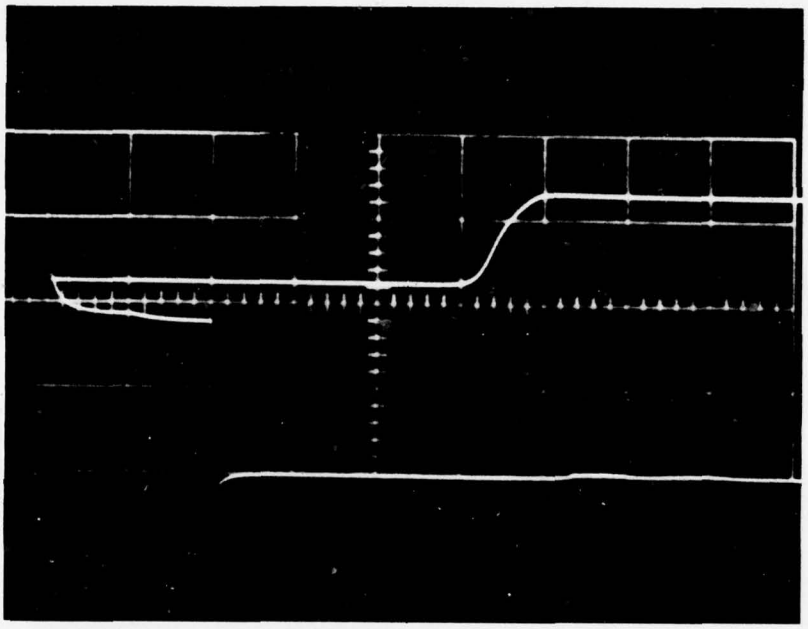
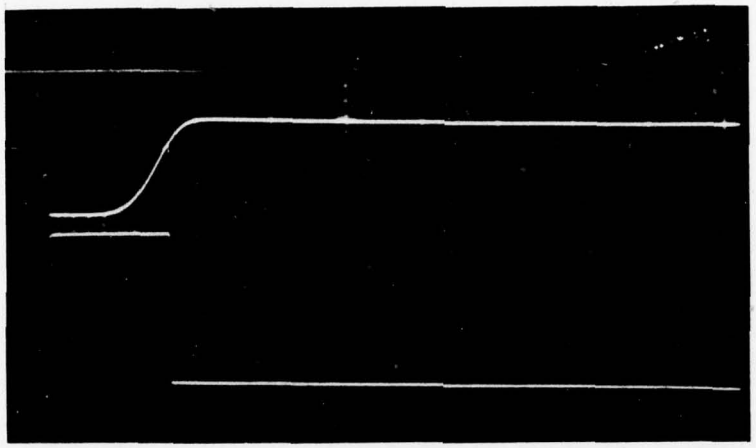
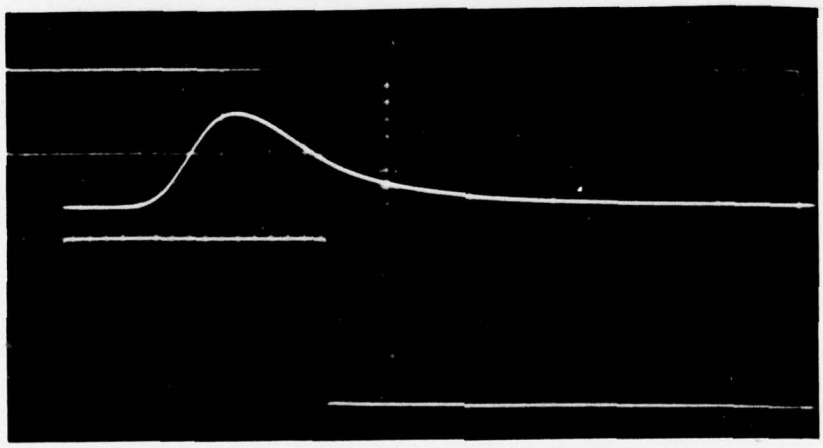


Figure 5. Oscilloscope Trace Showing Write Cycle Completed in Less Than 10 msec. Lower Curve is Charge Voltage, Upper Curve is Diffracted Signal Sensed by a Photodetector. A 1.5 msec Heat Pulse was Applied Between the Charge Pulse and the Onset of Diffraction. Time Base is 1 msec/div.



(a) Correct Heat Input (1.7 msec heat pulse)



(b) Excessive Heat Input (3.2 msec heat pulse)

Figure 6. Oscilloscope Traces Showing Relationship Between Diffracted Signal (Upper Trace) and the Develop Voltage (Lower Trace). Time Base is 1 msec/div.

can be charged and heated. In particular, unless the device is thermally biased at an elevated temperature, reducing the length of the heat pulse increases its required amplitude, ultimately reaching practical limitations such as (in the case of resistive heating) the voltage capacity of the transparent conductor. Furthermore, the required energy input is proportional to the active area of the device, compounding the problem for larger devices.

A more difficult question concerns the rate at which the PTP transducer can be repetitively written and erased. Not only is heat required for both developing and erasing the thermoplastic deformations, but as can be seen by the following argument, erasure requires greater heat input than development. To eliminate the surface defomations in the erase step, the electric field across the thermoplastic must be dissipated by decreasing the electrical resistivity of the thermoplastic. For a thermoplastic to be useful, however, it is necessary for the surface deformations to form in the develop step before the resistivity decreases and the fields collapse. Thus it follows that for erasure the thermoplastic must be heated to a higher temperature or maintained longer at the develop temperature than necessary for the develop step. Rapid cycling, therefore, is likely to require a larger portion of the cycle for erasure than for development.

For rapid cycling, heat can be applied in one or a combination of two modes, pulsed or continuous heating. If the cycle period is short, pulsed heating degenerates to continuous unless the heat can be removed from the substrate rapidly. By using a substrate having a high thermal conductivity, short heat pulses (1 msec or less), and liquid cooling at the rear surface of the substrate, it appears possible to record and erase continuously at frame rates as high as 10 frames/sec while maintaining a relatively low thermoplastic temperature [17].

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17. W.S. Colburn, C.C. Aleksoff, and I. Cindrich, Final Technical Report "Thermoplastic Modulator Development," Report No. 128700-10-F, Environmental Research Institute of Michigan, in preparation.

We used a repetitive cycling capability of our timing circuit to investigate the behavior of the PTP device under conditions of repetitive writing while biased at an elevated temperature. The temperature bias was provided by passing DC current through the transparent electrode. Figure 7 shows curves of the deformation and decay times of the deformations as a function of the input power for the methacrylate/styrene copolymer thermoplastic heated continuously at a power level of 2.4 watts/cm^2. At this bias level, we could write and erase recordings at the rate of four per second as shown by the curve in Figure 8, an oscilloscope trace of the first order diffracted intensity as a function of time. As in the rapid write experiments, the exposure was continuous to permit monitoring of the thermoplastic deformations by observation of the diffracted intensity. Figure 8 shows that upon the application of charge, the thermoplastic spontaneously deforms in 30 to 40 msec and then more slowly relaxes, with the deformations decaying in 100 to 200 msec. With continous heating, the cycle rate depends on the bias temperature and on the thermoplastic characteristics. A potential difficulty is that at a given temperature the decay rate of the deformation appears to be dependent on the spatial frequency [17]. We observed that after a few minutes of continuous cycling at the rates indicated in Figure 8, the thermoplastic surface developed course surface irregularities. The preliminary nature of our investigations into continuous cycling precluded attempts to discover and eliminate the source of degradation. We point out, however, that continous cycling forces the PTP medium into a mode for which it is not particularly well suited and for which alternative transducers appear to be available. Furthermore, rapid cycling abandons one of the prominent advantages of the PTP recording medium, its ability to retain an image indefinitely.

3.3 RESOLUTION

The PTP recording medium is well known to exhibit a bandpass response to spatial frequencies [9]. It was, therefore, necessary

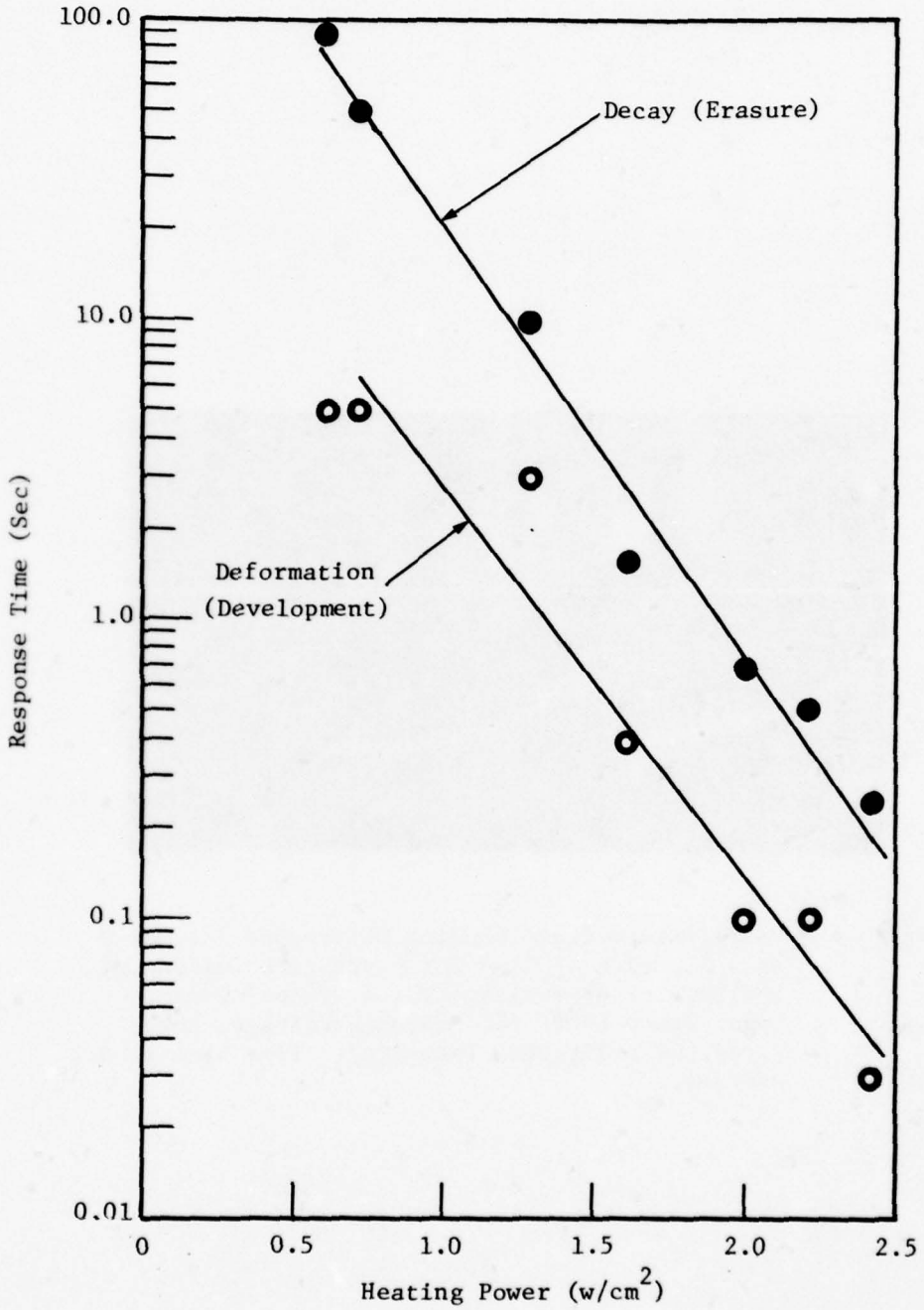


Figure 7. Deformation and Decay Times as Functions of Input Power For the Methacrylate/Styrene Copolymer Thermoplastic Under Conditions of Continuous Heating.

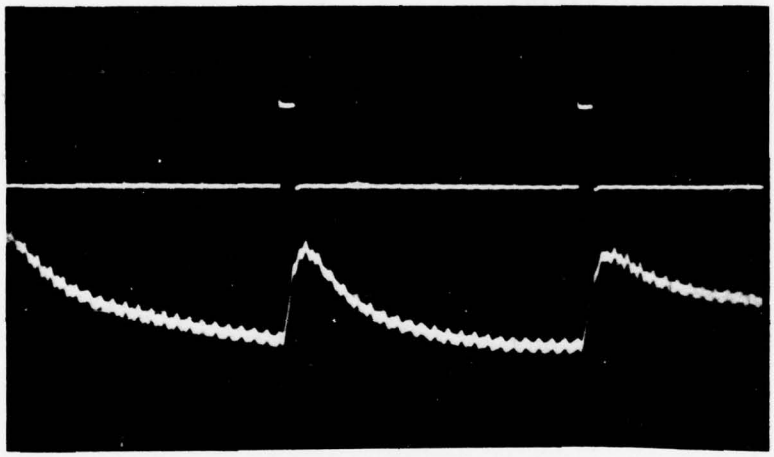


Figure 8. Oscilloscope Trace Showing Diffracted Intensity as a Function of Time for Repetitive Writing at the Rate of Approximately 2.5 cycles/second. Upper Trace Shows the Charging Voltage, Lower Trace the Diffracted Intensity. Time Base is 0.1 sec/div.

to overlay the image to be recorded with a grating to provide a frequency offset [7]. Most investigations of the PTP medium have been at spatial frequencies in excess of several hundred cycles/mm; in our investigations of the PTP transducer, we were interested in a response peaked near the frequency of our grating, 40 cycles/mm. Although we could have used a grating with a higher frequency, in our transducer investigations we imaged the grating onto the transducer and were thereby constrained by the capability of the available imaging lenses.

Since the center frequency of the pass band varies inversely with the thermoplastic thickness, we used relatively thick thermoplastic layers in our investigations. Figure 9 shows a curve of the frequency response of a typical PTP device used in our investigations. The peak response occurs near 50 cycles/mm with a bandwidth of 80 cycles/mm. The data shown in this curve were obtained by recording the interference pattern between two plane waves at different angles, and measuring the resulting diffraction efficiency. The interference patterns were recorded with parallel-plane charging at 750 v and at an exposure of 200 ergs/cm^2 at 633 mm wavelength. We were unable to obtain a direct measurement of the thermoplastic thickness, but note that the thermoplastic layer was formed by dip coating where the pulling rate was 18 cm/min and the coating solution had a thermoplastic concentration of 250 g per liter of solution.

To verify the resolution of the device as an incoherent-to-coherent transducer, we imaged a bar chart onto the photoconductor with the optical system shown in Figure 10. The bar chart was placed at the input plane of the optical system and illuminated with white light. The grating had a spatial frequency of 40 cycles/mm and was imaged onto the transducer with unity magnification. After the transducer had recorded the image, it was illuminated with a plane wave of coherent light at normal incidence. A lens behind the transducer formed the Fourier transform of the thermoplastic recording. At the transform

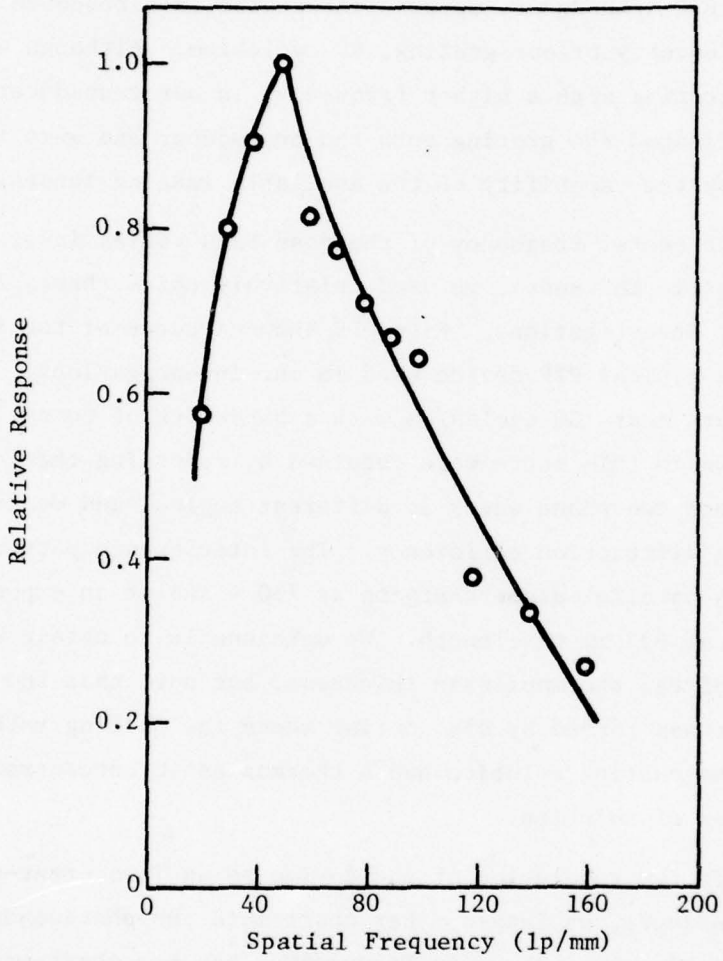


Figure 9. Bandwidth Curve of a Photoplastic Transducer with a Thick Thermoplastic Layer.

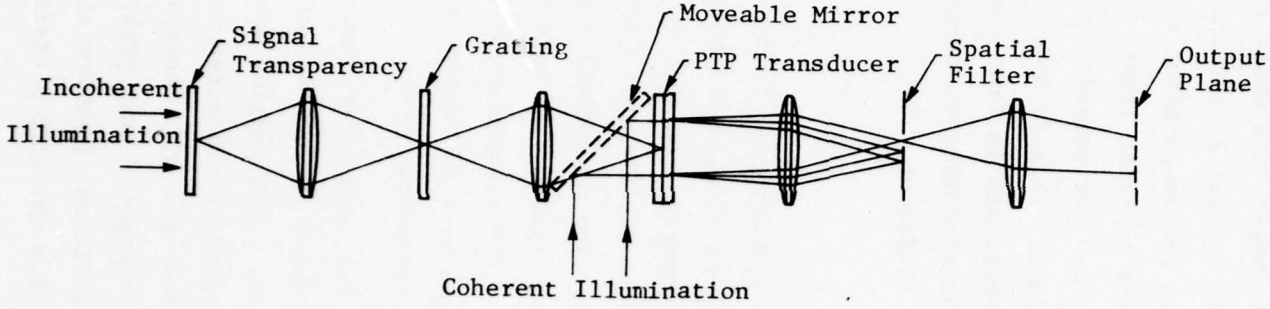


Figure 10. Configuration of the Optical System Used for Incoherent Write and Coherent Read.

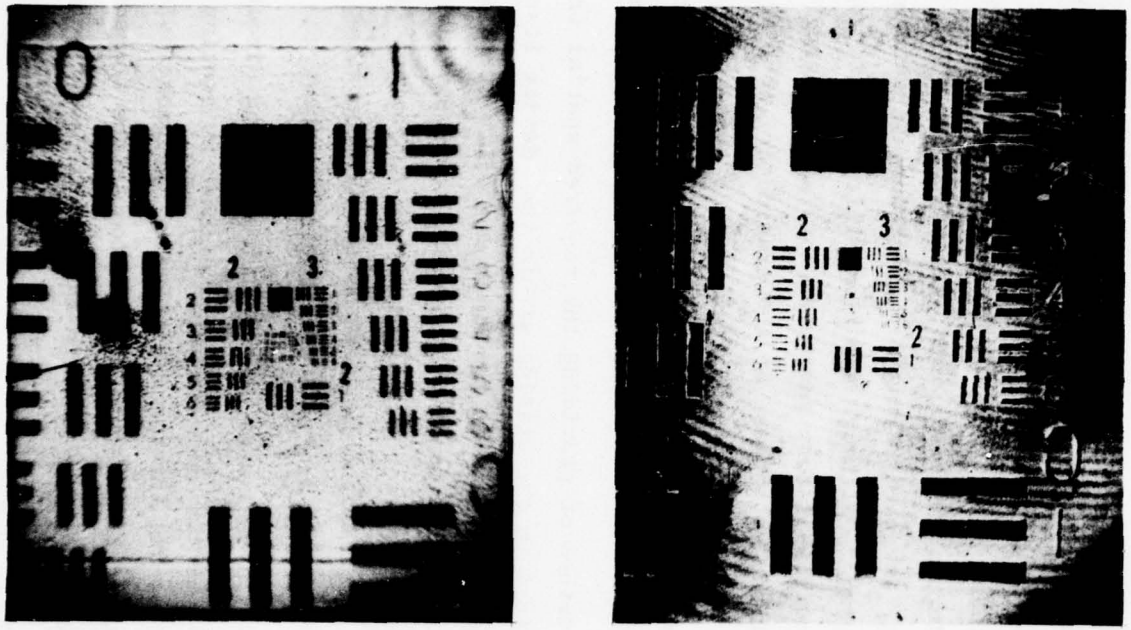
plane, a spatial filter removed all but one diffracted order, which formed an image at the output plane after passing through a final lens.

Figure 11 shows photographs made at the output plane of the bar chart; Figure 11a shows the chart imaged with white light through the entire optical system (without the spatial filter and with the transducer erased) and Figure 11b shows the image after it was recorded on the transducer and illuminated with coherent light. The finest set of bars in group 3 is just resolved, and corresponds to a frequency of 18 cycles/mm at the transducer plane. This is quite reasonable in light of the 40 cycle/mm grating frequency, and in fact from the discussion in Section 2, we would expect some intermodulation distortion at signal frequencies in excess of about 13 cycles/mm.

3.4 CRT INPUT

A useful mode of transducer operation is to derive the input data from a CRT. From a systems point of view, a TV camera/CRT combination forms a convenient and flexible input source that is reliable and readily available. The CRT is also a convenient device for transforming a one-dimensional time varying electrical signal into a two-dimensional space varying optical signal. The information displayed on the CRT can be transferred to the PTP transducer by means of an imaging lens, although a grating structure must be present at some point in the system to provide the necessary frequency offset.

We recorded information on the transducer from a CRT, but found that lengthy exposures were required owing to inefficient imaging conditions and low phosphor brightness. The imaging was inefficient primarily because we were demagnifying the CRT screen with a lens located at a relatively large distance from the CRT, where it intercepted only a small fraction of the phosphor output. This problem can be alleviated through the use of a more efficient (and somewhat more complex) imaging system, and by the use of a CRT with a small screen diameter.



(a) Incoherent Input Image (b) Coherent Output Image

Figure 11. Photograph of Images at the Output Plane, Showing the Input Image in Incoherent Light Before Recording and the Thermoplastic Image in Coherent Light After Recording.

3.5 SCREENING INVESTIGATIONS

Because of the bandpass nature of the frequency response of the PTP recording medium, it was necessary to overlay the image with a grating during the recording step. Several methods exist for adding the grating structure; in our investigations, we imaged the input information onto a grating, and then reimaged the grating and information onto the photoconductor. Although the flexibility of this approach made it well-suited to our laboratory investigations, the imaging step imposed certain restrictions on the use of the transducer. The principle restrictions were in the space-bandwidth product that could be accommodated by the imaging lens with a flat field and in the narrow depth of focus which required precise positioning of the transducer.

A more attractive method of providing the required spatial frequency offset would be to form the grating within the device itself as has been reported, for example, for the Ruticon [18]. Such a grating could have a relatively high spatial frequency and would simplify the imaging system that transfers the information in incoherent light to the transducer. We investigated two methods for incorporating the grating into the PTP device but achieved only partial success.

The first method we investigated was to etch a grating directly into the transparent electrode. This was accomplished by coating the electrode with photoresist and forming a grating in the photoresist layer. This grating structure was then transferred to the transparent electrode by an etching process and the remaining photoresist subsequently removed.

We used Shipley AZ-1350 photoresist and formed the photoresist grating as described in Table 1. The master grating was a silver halide

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18. N.K. Sheridon, "The Ruticon Family of Erasable Image Recording Devices", IEEE Trans. on Electron Devices, ED-19, p. 1003 (1972)

Table 1. Preparation of Photoresist Grating

Step 1	Clean substrate.
Step 2	Dry substrate at 70°C for 10 minutes.
Step 3	Coat substrate with photoresist. We used spin coating at a speed of 2000 rpm.
Step 4	Dry coating at 70°C for 10 minutes.
Step 5	Contact print a master grating onto photoresist, with illumination from a mercury arc.
Step 6	Develop photoresist for 1 to 2 minutes in AZ-1350 developer diluted 1:1 with water.
Step 7	Rinse in deionized water and dry at 70°C for 10 minutes.

absorption grating with a spatial frequency of 40 cycles/mm. After the photoresist grating was complete, it was inspected under a microscope for defects; if the grating was unsatisfactory, the photoresist was removed with acetone and the process was repeated.

After the grating was formed in the photoresist, it was transferred to the transparent electrode by a chemical etch. To etch the indium oxide, we used a solution of hydrochloric acid formed by diluting 37% HCl 1:1 with water. The diluted acid etched slowly enough to allow careful control of the process, which required about 14 minutes. After 8 minutes of etching, every 2 minutes we interrupted the process and measured the resistance in the direction transverse to the grating lines. When the resistance reached 50 kΩ, the etching was considered complete and the process was terminated.

We observed that the gratings in the transparent electrode tended to be of low quality. Although the photoresist gratings and coatings appeared quite uniform, the electrode grating was less uniform in appearance, and, in particular, appeared to have many scratches over the entire grating structure. Some of these scratches were deep enough to destroy the electrical continuity of the grating lines, which rendered large areas of the device inoperative. The cause of the scatches, which were not evident prior to the grating formation, is unclear.

Several devices were fabricated with gratings that had acceptable quality. These devices were coated with photoconductor and thermoplastic layers as described previously [7], and tested in an optical system. The refractive index mismatch between the transparent electrode and the photoconductor caused a certain amount of diffraction in the absence of a recording. Although the diffraction increased substantially when a recording was formed, we found that the surface deformations were due primarily to the charge modulation created by the grating structure alone, and that exposing the photoconductor to an intensity pattern

had little additional effect on the diffraction. The approach of forming the grating in the transparent electrode, therefore, did not appear to be a fruitful one.

Our second approach was to form an insulator grating on the surface of the transparent electrode prior to adding the photoconductor and thermoplastic layers. It was hoped that the grating lines would prevent charge injection from the transparent electrode to the photoconductor. As in the previous approach, the fabrication process began by forming a photoresist grating on the surface of the transparent electrode. The insulator grating was then formed by evaporating a thin layer of SiO_2 over the photoresist grating. When the remaining photoresist was stripped, only the SiO_2 that was deposited between the photoresist grating lines remained. The grating quality was rather poor, however, and it was difficult to ascertain whether the photoresist had been completely removed.

We coated several of these devices with photoconductor and thermoplastic layers, but did not obtain positive experimental results (although our tests were not exhaustive). If properly formed, the insulator grating should be effective at preventing the transfer of charge carriers from the transparent electrode to the photoconductor. The exposure creates hole-electron pairs within the photoconductor layer, however, which would tend to circumvent the insulating action of the grating.

A third approach, which appears somewhat more straightforward, is to form an absorption grating on the surface of the transparent conductor to modulate the incident illumination during exposure. The exposure in this case would have to occur with the light incident to the rear surface of the device in order to pass through the grating before reaching the photoconductor. Although time did not permit experimental investigation of this approach, establishing an integral grating in the PTP transducer remains a desirable objective to simplify the transducer application.

3.6 PTP DEVICE PERFORMANCE

We conclude this section on the device investigations with a brief discussion on the general performance of the PTP device. In addition to its capability for recording and erasing information in near real-time, the medium has a reasonable exposure sensitivity and good optical quality [7,19]. In comparison to other spatial light modulators, the PTP transducer is prominent for its high inherent resolution, its ability to retain an image indefinitely during readout, and its simplicity of construction. Its major limitations at this time are the thermoplastic lifetime and the cycling rate that can be maintained. We summarize in Table 2 the best reported performance parameters for PTP devices, and give typical parameters as well.

Potential applications of the PTP transducer are determined, in part, by the lifetime characteristics of the thermoplastic. Anderson et. al. [11] reported cycling capabilities in excess of 10^5 for styrene/methacrylate copolymers in electron beam systems, and photoplastic devices are beginning to approach that level of performance. Using a thermoplastic of polystyrene, Lo et. al. [20] were able to achieve typical lifetimes of 30,000 cycles, with a maximum published figure of 80,000 cycles. Other materials that have been tested have been limited to fewer cycles. A vinyl toluene thermoplastic has withstood over 8000 complete record/erase cycles [4], and a terpolymer similar to the styrene/methacrylate copolymer used in the transducer investigations has been tested to 5000 record/erase cycles [4], although in that test redundancy in the image extended the lifetime beyond the number of cycles that would be acceptable in the transducer application. Although we anticipate further improvements in thermoplastic lifetime with continued materials research, the current lifetime characteristics

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19. W.S. Colburn and B.J. Chang, "Photoconductor-Thermoplastic Image Transducer," Opt. Eng., To be published.

20. D.S. Lo, L.H. Johnson, and R.W. Honebrink, "Thermoplastic Recording," SPIE Proceedings on Practical Applications of Low Power Lasers, 92, San Diego, California, August 26-27, 1976.

Table 2. Typical and Best Performance Parameters of the PTP Recording Medium

Parameter	Typical Value	Best Reported Value	Reference
Minimum Exposure Energy	50-100 ergs/cm^2	20 ergs/cm^2	[7]
Resolution	1000 ℓp/mm	4100 ℓp/mm	[3]
Peak Contrast Ratio	100:1	200:1	[21]
Write Time	1-5 sec	7 msec	[19]
Cycle Period	10-60 sec	250 msec	[19]
Lifetime	10^3 cycles	8×10^4 cycles	[20]

21. S. Reich, Z. Rav-Noy, and A.A. Friesem, "Frost Suppression in Photoconductor-Thermoplastic Holographic Recording Devices," Appl. Phys. Lett. 31, 654 (1977).

are adequate in the context of an objective of an inexpensive and relatively simple transducer. In many applications, the number of cycles required is within the capabilities of existing materials. For other applications the device could easily be recoated when the number of write/erase cycles approaches the useful limit of the thermoplastic.

Investigators working with the PTP medium have occasionally reported observing what Lee [22] has termed a residual image (see also Refs. 5 and 23), the reappearance of a previously erased image in a subsequent recording. The residual image is a result of incomplete erasure of the photoconductor, and can form by simply charging and heating the medium; exposure is not necessary. The residual image is clearly undesirable as its presence degrades the desired recording. It appears to be caused by trapped charges, and can be minimized by erasing at high temperatures, illuminating the photoconductor prior to erasure, or by increasing the electron mobility in the photoconductor. In our transducer investigations, the residual image did not occur, possibly owing to the low spatial frequencies at which the transducer operated.

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22. T.C. Lee, N. Marzwell, F.M. Schmit, and O.N. Tufte, "Development of Thermoplastic-Photoconductor Tape for Optical Recording," To be published.

23. T. Saito, S. Oshima, T. Honda, and J. Tsujiuchi, "An Improved Technique for Holographic Recording on a Thermoplastic Photoconductor," Opt. Commun. 16, 90 (1976).

4
OPTICAL PROCESSING WITH THE PTP TRANSDUCER

We continued the matched filter investigations begun previously [7] and integrated the transducer with the Advanced Optical Processor developed under a parallel program [6]. In the matched filter investigations we correlated successive transducer recordings with a previous recording. The filter was recorded either on a Kodak 649F Microflat plate, or for convenience, on a second PTP device. A correlation peak formed at the transform plane of a lens placed behind the filter on the axis of the reference beam used to record the filter, as shown in Figure 12. To measure the signal-to-noise ratio and the size of the correlation peak, we scanned the spot with a 50 μm diameter fiber optic probe located at the image plane of a microscope objective. Figure 13 shows a typical scan of the peak made when the transducer had been erased and rewritten several times after the filter had been recorded.

An important test is to translate the input data, reimage and rerecord it on the transducer, and observe the translation of the correlation peak. We verified that the correlation peak moved when the input data was moved, but observed that an additional peak remained at the center of the correlation (output) plane. Although we did not determine the source of the additional correlation peak, it apparently represents correlation of the noise and aberrations introduced by the various optical surfaces within the portion of the optical system illuminated by coherent light to record the filter. Since these surfaces are unchanged when the transducer image was changed, a correlation signal caused by them would likewise be unchanged.

As a final experiment to test the PTP transducer, we added it to the Advanced Optical Processor developed under a separate, parallel

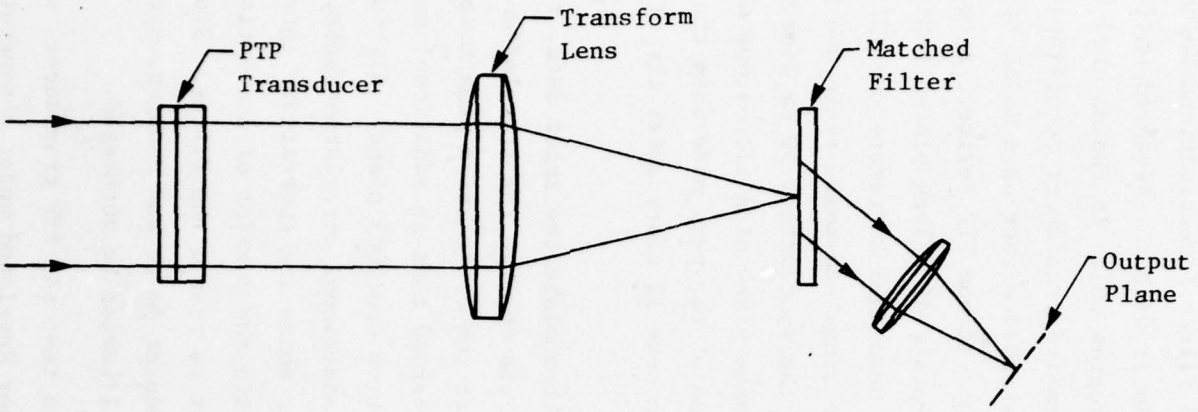

Figure 12. Configuration of the Matched Filter Processor with the PTP Transducer at the Input Plane.

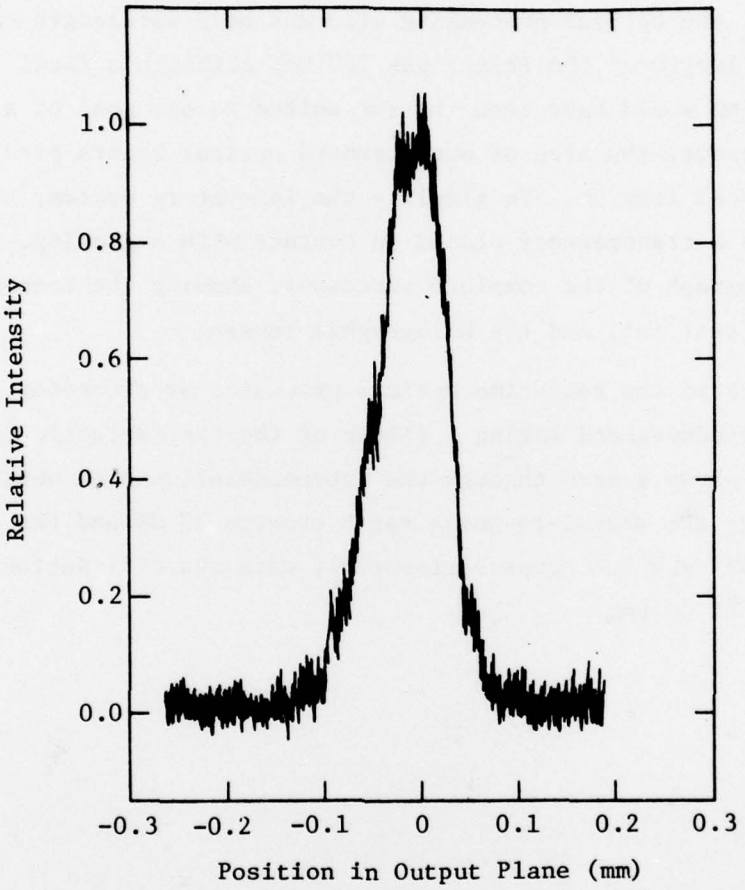

Figure 13. Correlation Peak at the Output Plane of a Matched Filter Processor After the Signal Had Been Erased and Rewritten on the Transducer.

program [6,24,25]. This processor is a laboratory version of a compact, lightweight processor that uses reflective holographic lenses as its optical components. Figure 14 shows the configuration of the optical processor with the PTP transducer to provide an input signal. Because the hologram lenses were recorded in dichromated gelatin at a wavelength of 514 nm, the optical processing also was at a wavelength of 514 nm. The focal length of the lenses was 500 mm; although a focal length of about 100 mm would have been better suited to our goal of a very compact processor, the size of our standard optical mounts precluded shorter focal lengths. To simplify the laboratory system, the input signal was a transparency placed in contact with a grating. Figure 15 is a photograph of the complete processor, showing the transducer in its argon test cell and the holographic lenses.

We tested the real-time optical processor by recording an image on the transducer and making a filter of the thermoplastic image. Figure 16 shows a scan through the autocorrelation peak obtained with the filter; the signal-to-noise ratio exceeds 30 dB and the 3dB spot width is 47 μm, which compares favorably with the diffraction-limited spot size of 44 μm.

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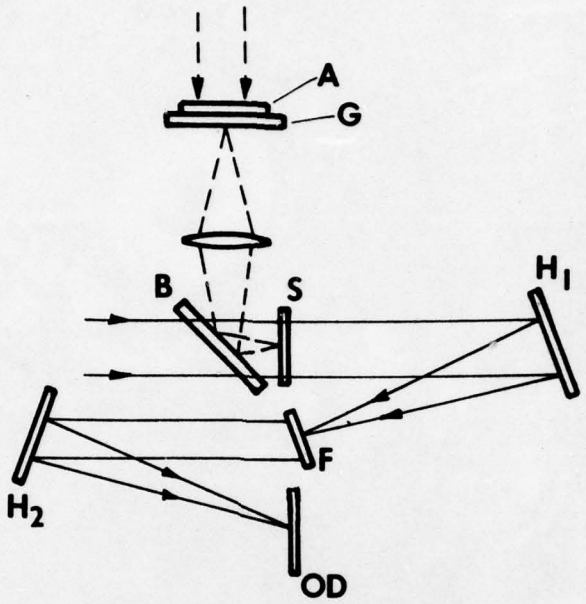
24. J.R. Fienup, W.S. Colburn, B.J. Chang, and C.D. Leonard, "Compact Real-Time Matched-Filter Optical Processor," Proc. SPIE 118, Optical Signal and Image Processing, p. 21 (August 1977).

25. J.R. Fienup and C.D. Leonard, "Holographic Optics for a Matched-Filter Optical Processor," Submitted for publication to Applied Optics.



A Signal Transparency

G Grating

B Beamsplitter

S PTP Transducer at the Signal Plane

H_1 and **H_2** Holographic Lenses

F Matched Filter

OD Output Plane

Figure 14. Configuration of the Real-Time Advanced Optical Processor.

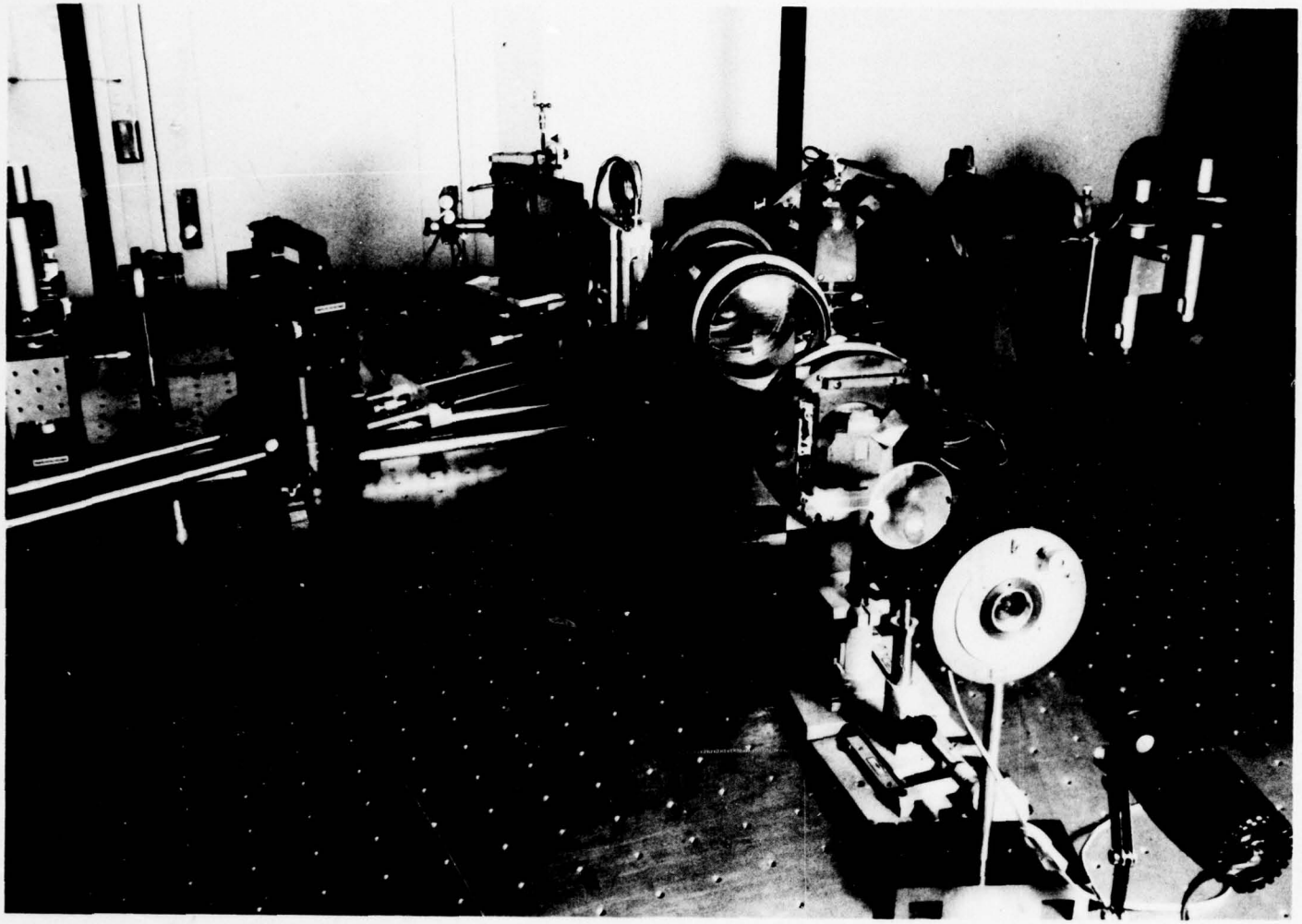


Figure 15. Photograph of the Advanced Optical Processor with the PTP Transducer.

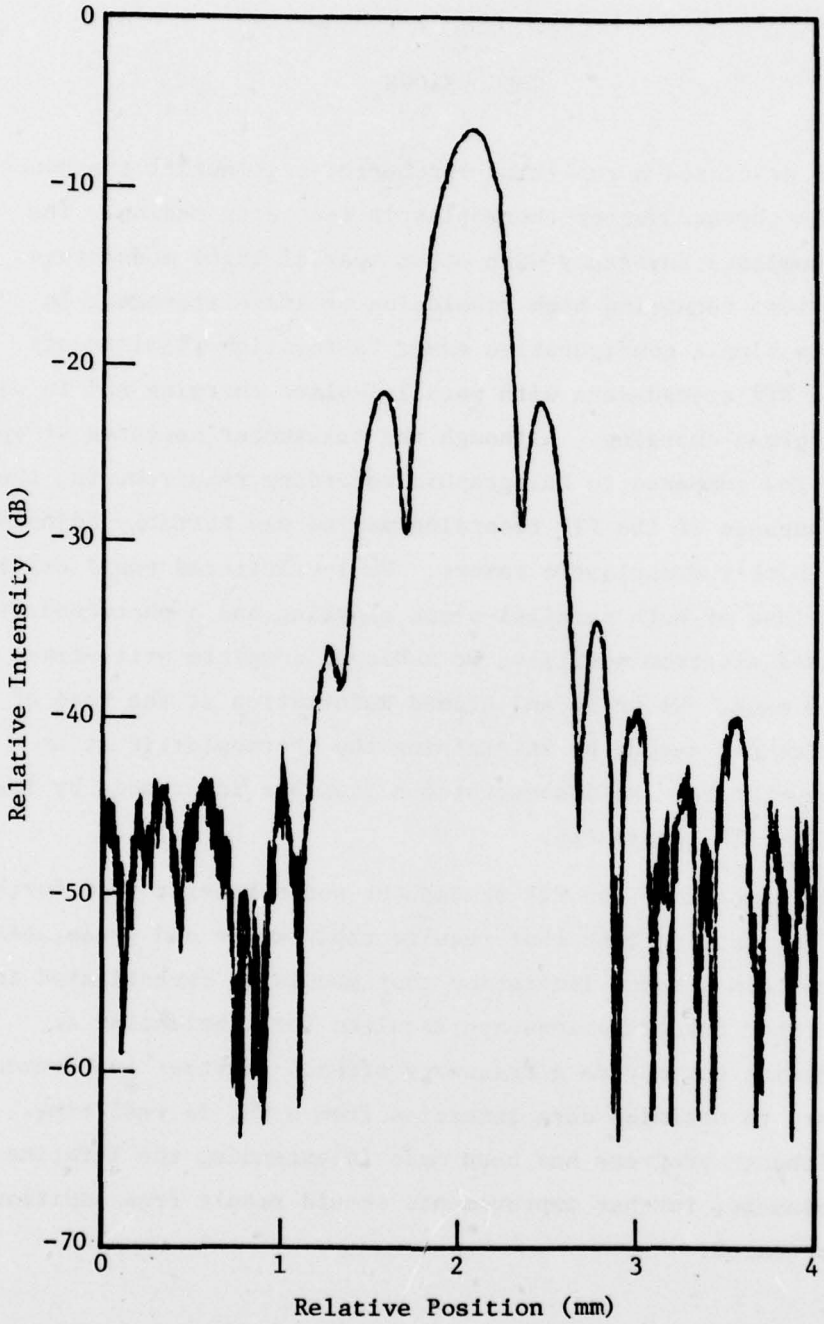


Figure 16. Autocorrelation Peak Achieved with a Matched Filter in the Advanced Optical Processor with the PTP Transducer as Input. (Output Plane is Magnified 6x).

5
CONCLUSIONS

We have developed a real-time incoherent-to-coherent transducer that uses the photoconductor-thermoplastic recording medium. The transducer compares favorably with other spatial light modulators for applications requiring high resolution or image storage. In addition, its simple configuration eases fabrication requirements. We investigated PTP transducers with parallel-plane charging and in some cases with corona charging. Although the transducer operates at spatial frequencies low compared to holographic recording requirements, the frequency response of the PTP recording medium was suitably adjusted by the use of thick thermoplastic layers. We investigated rapid writing, and with the use of both parallel-plane charging and a photoconductor with increased electron mobility, we achieved complete write-times of less than 10 msec. We wrote and erased information at the rate of several cycles per second by maintaining the thermoplastic at an elevated temperature. We demonstrated a flexible input mode by imaging a CRT onto the PTP transducer.

Certain aspects of the PTP transducer would benefit from further research. For applications that require rapid write and erase, heating requirements form a major limitation that should be investigated in detail. Further investigations are required for fabricating an integral grating to provide a frequency offset. Further improvements are necessary to optimize data insertion from a CRT in real-time. Finally, although progress has been made in extending the lifetime of the thermoplastic, further improvements should result from additional materials research.

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